

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.



Dual Nozzle Aerodynamic And Cooling Analysis Study

Contract NAS 8-33553
Bi-Monthly Progress Report 33553-M-10
July 1980

Prepared For:
National Aeronautics And Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

By:
G. M. Meagher

(NASA-CR-161525) DUAL NOZZLE AERODYNAMIC
AND COOLING ANALYSIS STUDY Monthly Progress
Report, 1 May - 30 Jun. 1980 (Aerojet Liquid
Rocket Co.) 25 p HC A02/MF A01 CSCI 21H

N80-28429

Unclas
G3/20 28265



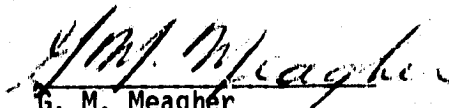
Aerojet
Liquid Rocket
Company

DUAL NOZZLE AERODYNAMIC AND
COOLING ANALYSIS STUDY


Bi-Monthly Technical Progress Narrative 33553 M10
Contract NAS 8-33553

10 July 1980

Prepared by


G. M. Meagher
Project Engineer

Approved by


J. W. Salmon
Program Manager

Prepared for

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

By

Aerojet Liquid Rocket Company
Sacramento, California

FOREWORD

This is the tenth Progress Report submitted for the Dual Nozzle Aerodynamic and Cooling Analysis Study per the requirements of Contract NAS 8-33553. The work is being performed by the Aerojet Liquid Rocket Company for NASA-Marshall Space Flight Center. The contract was initiated 9 July 1979. This report covers the period from 1 May 1980 to 30 June 1980.

The program consists of geometric, aerodynamic flow field, performance prediction, and heat transfer analyses for two advanced chamber/nozzle concepts applicable to advanced earth-to-orbit engine systems. The concepts to be modeled and analyzed are the dual throat and dual expander nozzles.

The NASA-MSFC Project Manager is Mr. F. W. Braam. The ALRC Program Manager is J. W. Salmon, and the Project Engineer is Mr. G. M. Meagher.

PRECEDING PAGE BLANK NOT FILMED

TABLE OF CONTENTS

	<u>Page</u>
I. Introduction	1
II. Technical Progress Summary	2
A. Task I - Aerodynamic Model and Performance Prediction Improvement (Dual Throat Engine)	2
B. Task II - Preliminary Geometric Analysis (Dual Expander Engine)	6
C. Task III - Preliminary Flow Field Analysis (Dual Expander)	6
D. Task IV - Preliminary Heat Transfer Analysis	6
E. Task V - Data Analysis	11
III. Current Problems	11
IV. Work Planned	11
A. Task I	11
B. Task II	11
C. Task III	12
D. Task IV	12
E. Task V	12
Reference	13
Appendix A	14

PRECEDING PAGE BLANK NOT FILMED

LIST OF TABLES

<u>Table No.</u>		<u>Page</u>
I	Secondary Nozzle Contour Optimization Results	4

LIST OF FIGURES

<u>Figure No.</u>		<u>Page</u>
1	Program Schedule	3
2	Effect of Nozzle Inlet Conditions on the Momentum Thickness for a Cooled Nozzle Wall	5
3	Dual Throat Secondary Nozzle Contour Comparison	7
4	Dual Expander Baseline Design	8
5	Dual Expander Secondary Throat Region	9
6	Dual Expander Prototype Case	10

I. INTRODUCTION

Propulsion systems for such future vehicles as the Single-Stage-to-Orbit (SSTO) and Heavy Lift Launch Vehicle (HLLV) may embrace such capabilities as dual-mode operation and in-flight changes in area ratio for altitude compensation. These vehicles benefit from dual-mode operation through reduced vehicle volume by taking advantage of high bulk density propellants in one mode and low density but higher performance propellants in the other mode. Area ratio change during flight provides an increase in performance as ambient pressure decreases with altitude.

Dual nozzle engines combine both operating capabilities in a single design. Their dual combustors allow use of two propellant combinations and, with their two separate nozzle throats and a fixed nozzle exit area, allow for a shift in area ratio without resorting to nozzle translating mechanisms.

Two types of dual nozzle designs have been conceived -- the dual throat and the dual expander. An engine system preliminary analysis using the dual throat concept was performed during Contract NAS 8-32967 to examine potential power cycles and generate parametric data. A preliminary performance prediction methodology was developed with an aerodynamic bleed flow computer model. This model was formulated by using the results of cold flow tests conducted with a subscale dual throat thruster configuration (NAS 8-32666). The dual expander engine concept has received less formal analysis. Some preliminary engine system parametric data has been generated and a conceptual baseline engine system has been formulated. The tasks to be conducted in this study will expand and deepen previous work on both of these concepts.

The objective of this program is to expand and extend the analysis models and parametric studies which have been previously performed for both the dual throat and dual expander engine concepts. This will be accomplished within five basic tasks, consisting of: (1) improvement to the existing dual throat aerodynamic and performance prediction computer model, (2) preliminary

I, Introduction (cont.)

geometric analysis of the dual expander concept, (3) preliminary flow field analyses of the dual expander concept, (4) further preliminary heat transfer analysis of both concepts, and (5) engineering analysis of data from the NASA/MSFC hot-fire testing of a dual-throat thruster model thrust chamber assembly. A sixth task has been created to incorporate the following reporting requirements: program plan, monthly progress reports, study reviews and technical briefings, and a final report.

II. TECHNICAL PROGRESS SUMMARY

The overall progress on the program is indicated in Figure 1.

A. TASK I - AERODYNAMIC MODEL AND PERFORMANCE PREDICTION IMPROVEMENT (DUAL THROAT ENGINE)

A new approach has been developed to calculate the boundary layer loss during Mode II operation. This new approach is still based on using the procedures for calculating boundary layer loss as described in Appendix B of CPIA No. 178 (Ref. 1).

The previous monthly report stated that a boundary layer loss of 3.7% had been calculated through a rigorous method involving use of the BLIMP computer program. This boundary layer loss included the effect of increased propellant enthalpy as the result of regen cooling increasing the I_{sp} ODE value. It was also stated that the simplified method developed under Contract NAS 8-32967 predicted a boundary layer loss of 3.6%. The simplified method was found to be in error because it did not take into account the increase in I_{sp} ODE as a result of increased propellant enthalpy. In actuality, the simplified method over-predicted the boundary layer loss.

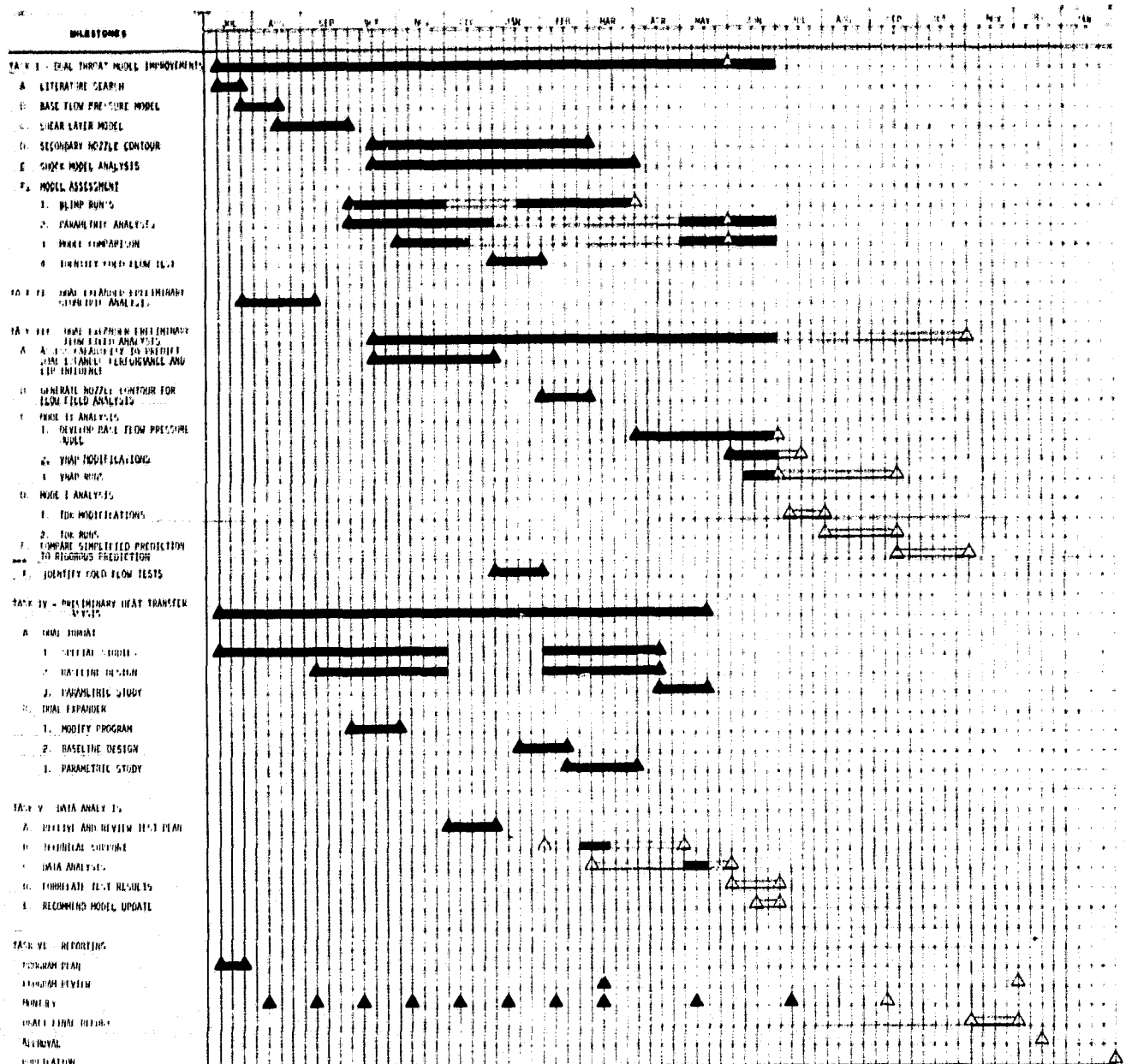


Figure 1. Program Schedule

II, A, Task I - Aerodynamic Model and Performance Prediction Improvement (Dual Throat Engine) (cont.)

The new approach makes use of the RTHETA input parameter which accounts for the influence of nozzle inlet geometry -- chamber length-to-diameter ratio (L/D^*), contraction ratio (r_c), inlet angle (α_i) -- on the momentum thickness used in calculating thrust loss. This influence is shown in Figure 2. A correlation was developed which relates the momentum thickness development during Mode II operation for a dual throat nozzle to a conventional nozzle by choosing the proper RTHETA value. This correlation was based on the BLIMP results and requires the momentum thickness at the plume impingement point as calculated by the aerodynamic bleed flow model.

This new approach also takes into account the increase in the I_{sp} ODE due to increased propellant enthalpy from regen cooling.

A parametric analysis was performed to investigate the effect of optimizing the secondary nozzle contour for either Mode I or Mode II. Table I shows the results of this analysis. The nozzle divergence efficiency (η_{DIV}) changes slightly -- approximately 0.4% for a particular mode of operation. Thus, optimizing the secondary nozzle contour for either Mode I or Mode II will not significantly change engine performance.

TABLE I.

Secondary Nozzle Optimized	Mode I $r_c=45:1$		Mode II $r_c=222:1$	
	MODE I	MODE II	MODE I	MODE II
η_{DIV}	.991	.988	.982	.985

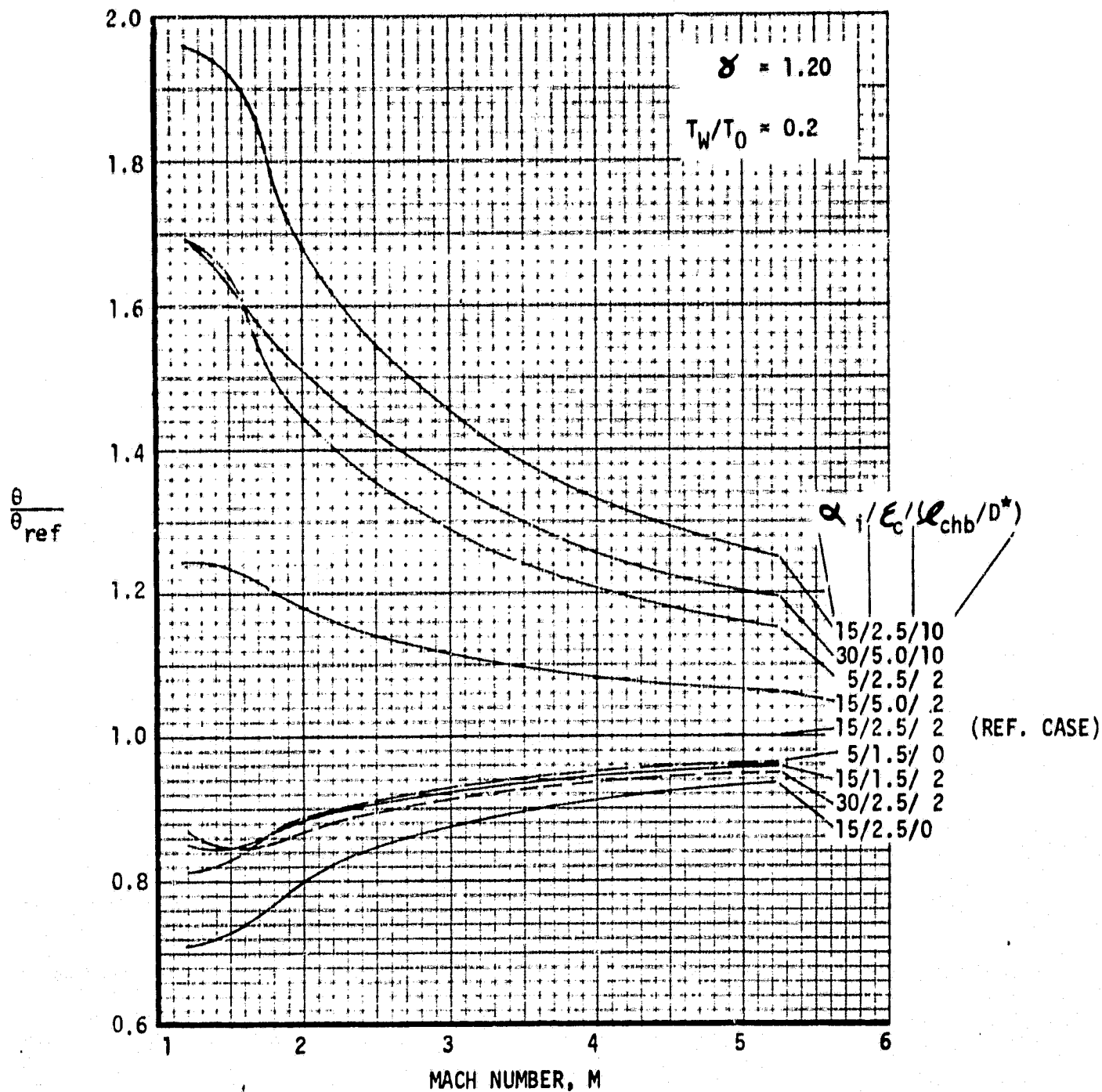


Figure 2. Effect of Nozzle Inlet Conditions on the Momentum Thickness for a Cooled Nozzle Wall

II, A, Task I - Aerodynamic Model and Performance Prediction Improvement (Dual Throat Engine) (cont.)

The secondary nozzle contour optimized for Mode II was generated by using the techniques of RAO, as described in the previous monthly reports. Figure 3 shows the difference in nozzle contours at the Mode II area ratio.

B. TASK II - PRELIMINARY GEOMETRIC ANALYSIS (DUAL EXPANDER ENGINE)

Completed.

C. TASK III - PRELIMINARY FLOW FIELD ANALYSIS (DUAL EXPANDER)

Work is continuing on the aerodynamic bleed flow model for use during Mode II operation. A problem statement for the model is given in Appendix A.

Work has begun on modifying the VNAP program to calculate thrust and specific impulse. VNAP will be used to determine the flow field in the conical section of the secondary nozzle contour. This flow field will be used in both Mode I and Mode II flow field analyses. Figures 4 and 5 show the baseline geometry that will be used in VNAP.

Work was also started on a prototype case for simulating Mode II operation. A constant supersonic start line at the exit of the conical section was assumed; also the free boundary expansion from the primary nozzle lip was represented by a straight line. A sketch of the configuration is shown in Figure 6. The purpose of this prototype case is to try to identify as early as possible any potential problems from using VNAP for the Mode II parametric analysis.

D. TASK IV - PRELIMINARY HEAT TRANSFER ANALYSIS

Completed.

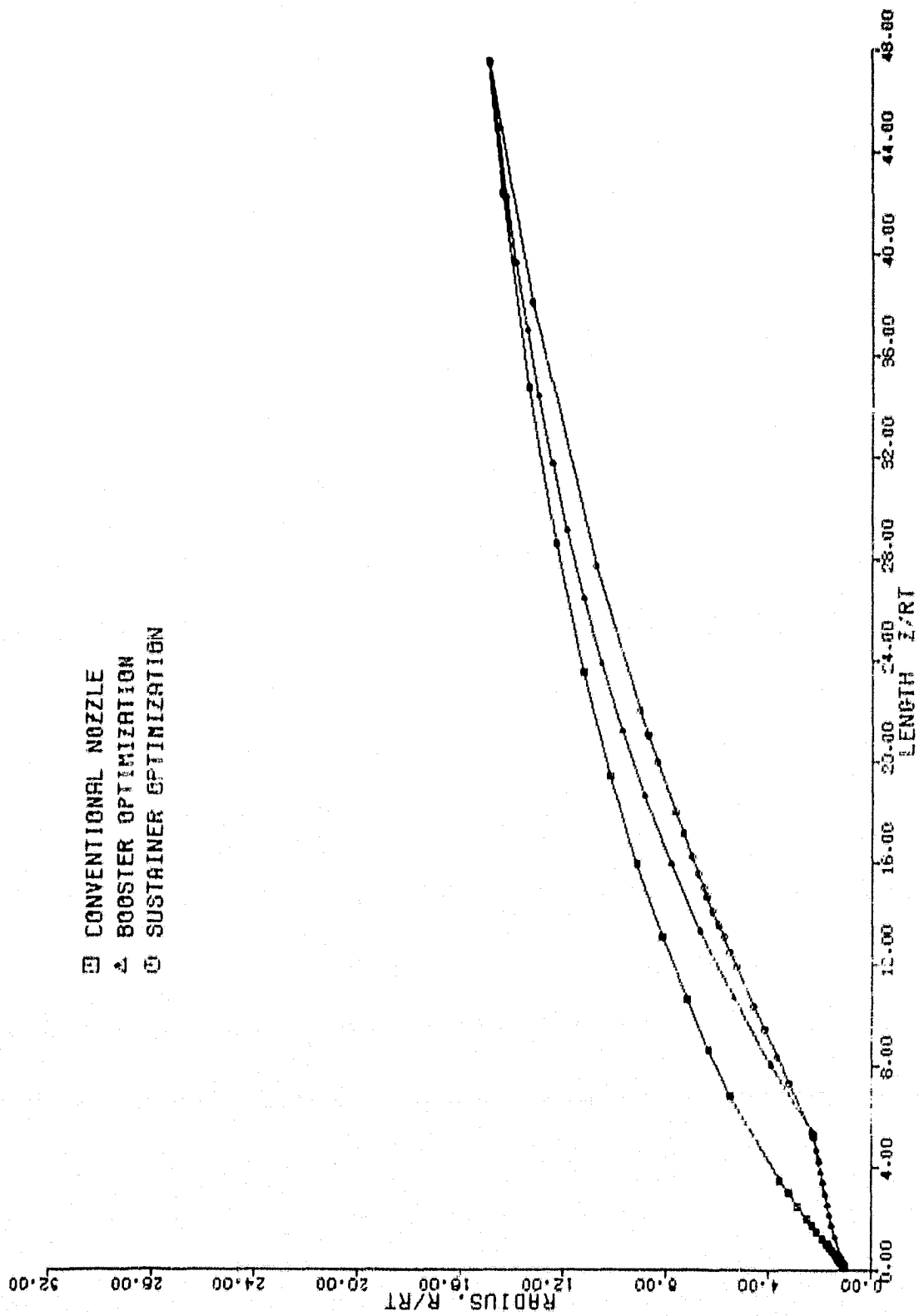


Figure 3. Dual Throat Secondary Nozzle Contour Comparison

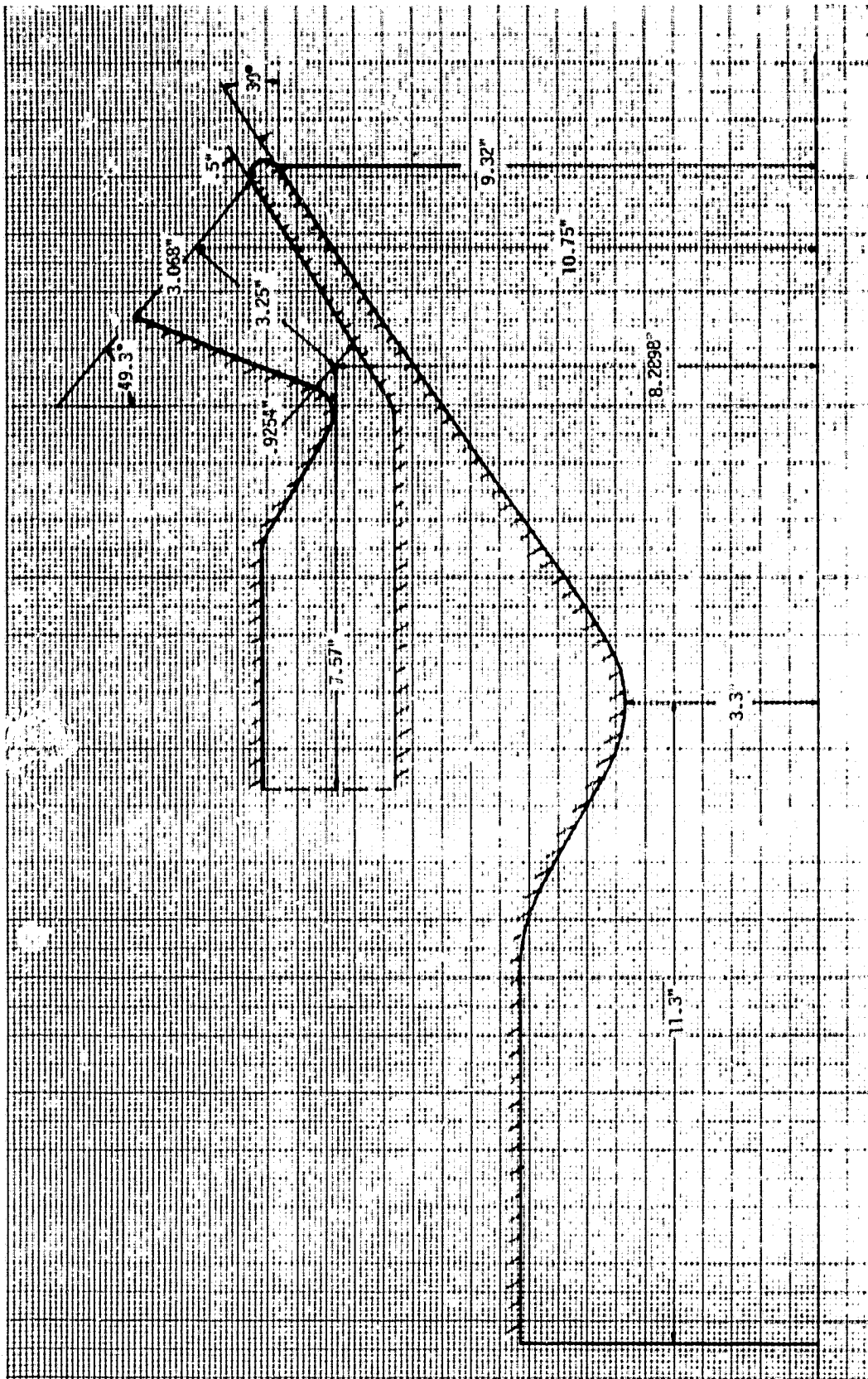


Figure 4. Dual Expander Baseline Design

ORIGINAL PAGE IS
OF POOR QUALITY

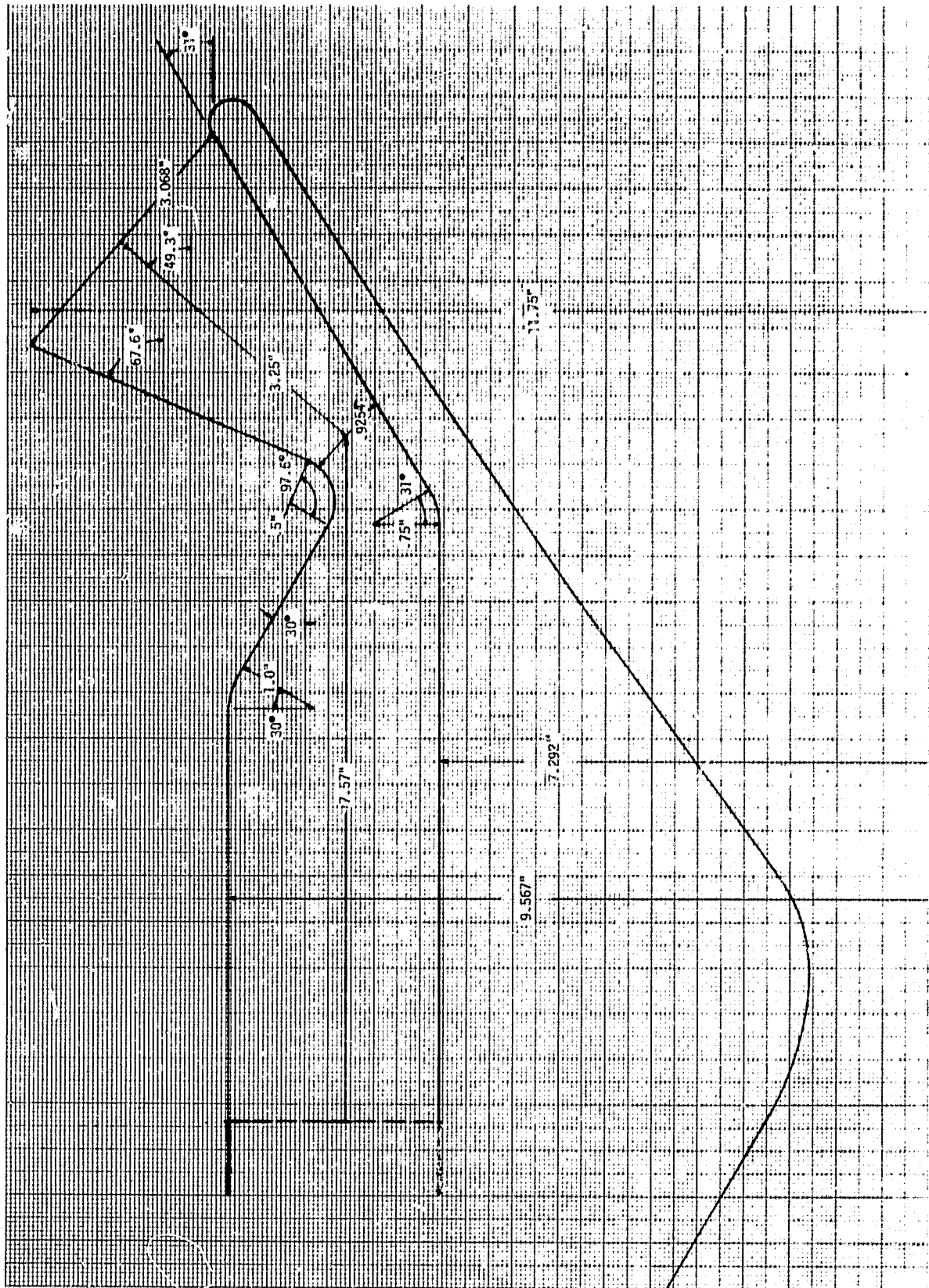


Figure 5. Dual Expander Secondary Throat Region

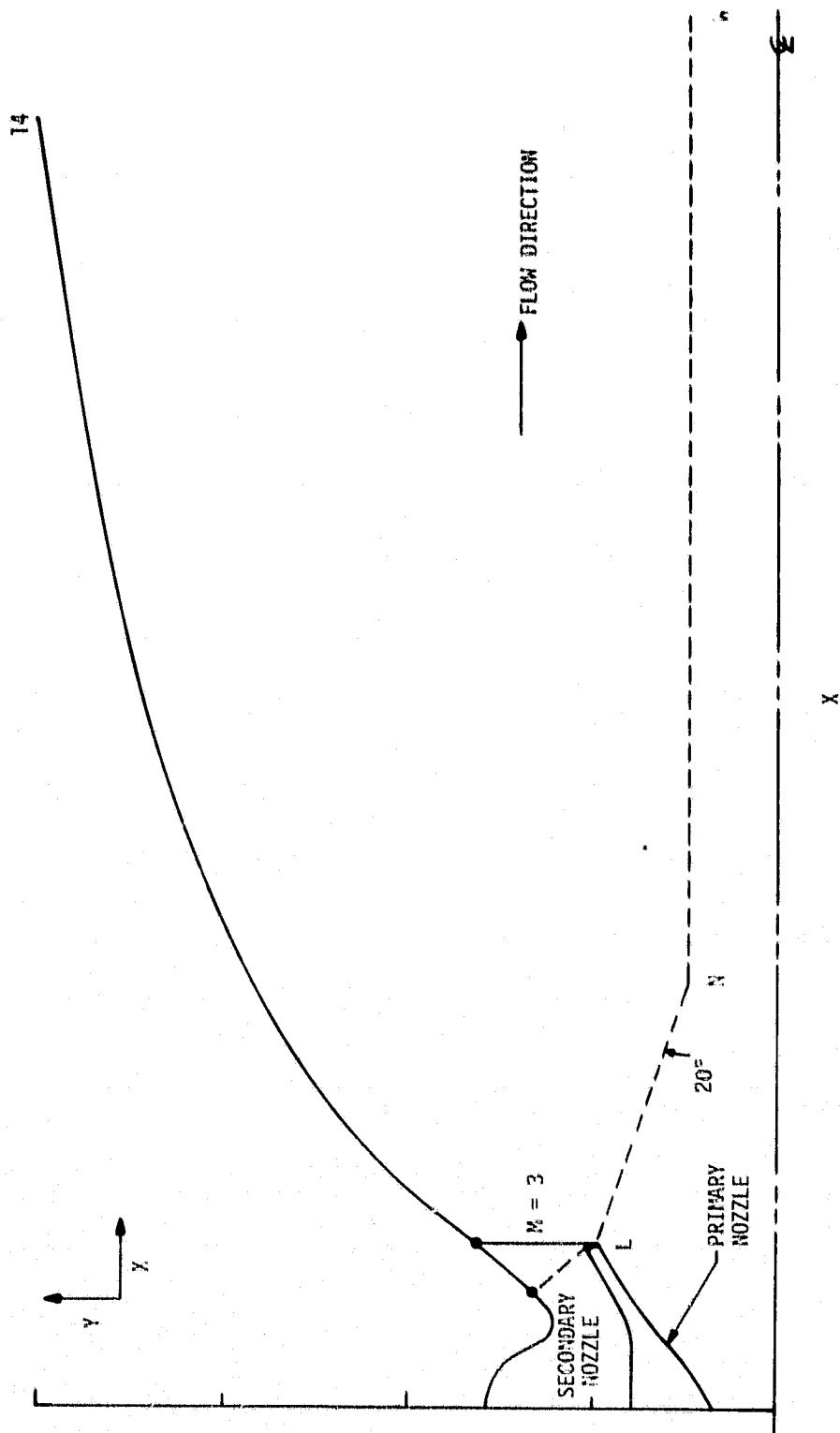


Figure 6. Dual Expander Prototype Case

II, Technical Progress Summary (cont.)

E. DATA ANALYSIS

Testing has been completed and is being processed for transmittal to ALRC.

III. CURRENT PROBLEMS

TASK I

Difficulties are still being encountered in completing the remaining BLIMP runs. Discussions between the NASA Project Manager and ALRC are being conducted in an effort to resolve these difficulties.

TASK III

The subcontractor has fallen behind schedule by approximately one month for completing the aerodynamic bleed flow model. The subcontractor will present a recovery plan on 18 July 1980 at ALRC.

IV. WORK PLANNED

A. TASK I

1. Resolve BLIMP difficulty issue.
2. Finish incorporating VNAP and BLIMP results into the simplified methodology.

B. TASK II

Completed.

IV, Work Planned (cont.)

C. TASK III

1. Complete dual expander bleed flow model.
2. Complete VNAP modifications.
3. Start TDK modifications.
4. Start Mode II VNAP simulations.
5. Conduct bleed flow model technical review at ALRC.

D. TASK IV

Completed.

E. TASK V

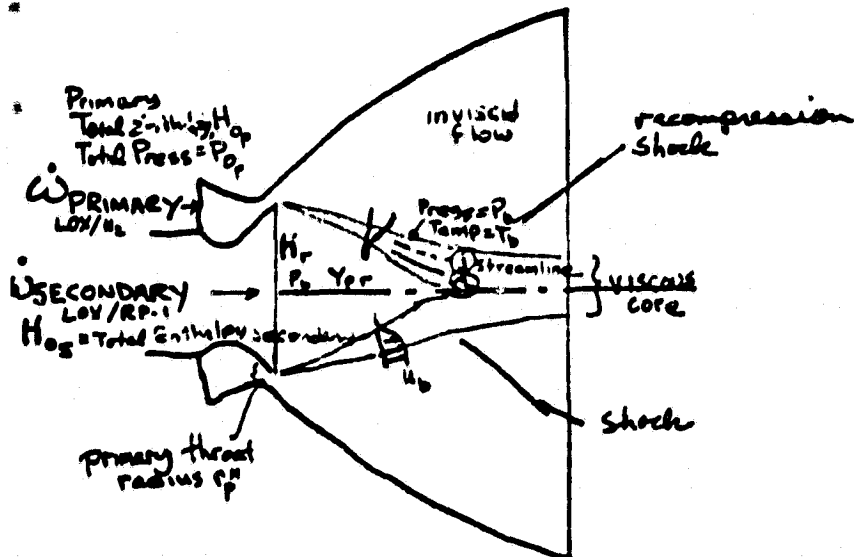
Analyze any test data received.

REFERENCES

1. Pieper, J. L., ICRPG Liquid Propulsion Thrust Chamber Performance Evaluation Manual, CPIA No. 178, September 1968.

APPENDIX A

Dual Expander - Korst Base Pressure Solution [Mode II Operation] Axisymmetric Flow



normalized velocity $\phi = \frac{u}{u_b} = \frac{1}{2}(1 + \operatorname{erf} \eta)$
 $\eta = \frac{\sigma y}{x}$

R = universal gas const.

1. Specify Gas Properties; $C_{p, \text{secondary}}$, $C_{p, \text{primary}}$, γ_s , γ_p , MW_s , MW_p note $R_p = \frac{R}{MW_p}$

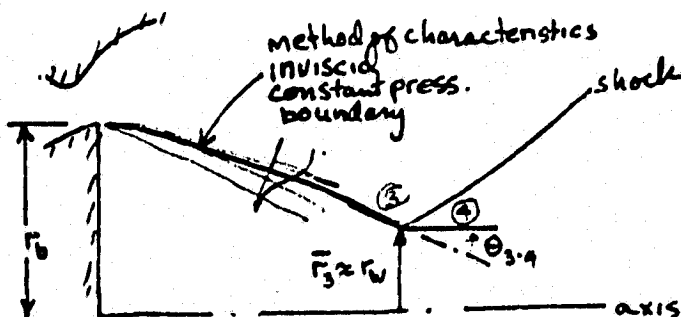
2. Guess base pressure ratio $\frac{P_b}{P_0}$

outer edge temp T_b : $\frac{T_b}{T_0} = \left(\frac{P_b}{P_0}\right)^{\frac{\gamma_p - 1}{\gamma_p}}$

Mach No. $M_b = \left(\frac{2}{\gamma_p - 1}\right)^{1/2} \left[\frac{1 - T_b/T_{0p}}{(T_b/T_{0p})}\right]^{1/2}$

Crocco No. C_b : $C_b^2 = 1 - \frac{T_b}{T_0}$

3.



Calculate constant pressure inviscid jet boundary extending toward the axis until radius of boundary r_3 is equal to empirical wake radius r_w

ORIGINAL PAGE IS
OF POOR QUALITY

Minyator :
assumption

$r_w = 0.5 r_b$

4. Calculate flow angle $\theta_{3,4}$ for turning the potential flow parallel to the axis of symmetry
From Oblique shock relations calculate P_4/P_b

5. Calculate from Recompression Criterion total pressure on "d" streamline, P_{0d} ; using Nash factor $N(\approx .4)$

$$\frac{P_{0d}}{P_b} = N \left(\frac{P_4}{P_b} \right) + (1-N)$$

6. Guess recirculation Enthalpy ratio: H_r/H_{0p}
Guess recirculation mass fraction of primary gas:
 Y_{Pr} (note: $Y_{Pr} = \left(\frac{P_p}{P_b} \right)^r$)
(also: $Y_{Sr} = 1 - Y_{Pr}$)

7. Calculate the ratio of specific heats for recirculation region, also C_{vr} and C_{pr}

$$C_{pr} = C_{p_{Sec}}(1 - Y_{Pr}) + C_{p_{Primary}} Y_{Pr}$$

Gas const. in recirculation region

$$R_r = R \left[\frac{(1 - Y_{Pr})}{MW_s} + \frac{Y_{Pr}}{MW_p} \right]$$

R = universal gas const.

$$C_{vr} = C_{pr} - R_r \quad , \quad \gamma_r = \frac{C_{pr}}{C_{vr}}$$

8. Estimate the ratio of specific heats on the "d" streamline

First guess $\phi_d = 0.6$

$$\bar{\gamma}_d = \frac{\gamma_r (1 - \phi_d) + \gamma_p \frac{C_{ve}}{C_{vr}} \phi_d}{(1 - \phi_d) + \frac{C_{pe}}{C_{pr}} \frac{\gamma_r}{\gamma_p} \phi_d}$$

9. Calculate estimated Crocco no. for "d" streamline

$$C_d^2 = 1 - \left(\frac{1}{P_{od}/P_b} \right)^{\bar{\gamma}_d/(\bar{\gamma}_d - 1)}$$

note: $C_d^2 = \frac{u^2}{2C_p T_b} = 1 - \frac{T}{T_b}$
 $= 1 - \left(\frac{P}{P_b} \right)^{\frac{\gamma}{\gamma-1}}$

10. Calculate velocity ratio for "d" streamline, $\phi_d = u/u_b$

$$\phi_d = \frac{1}{2} \left(\frac{C_d}{C_b} \right) \left[\left(\frac{C_d}{C_b} \right) \left[1 - \left(\frac{H_r}{H_{op}} \right) \right] + \sqrt{\left(\frac{C_d}{C_b} \right)^2 \left[1 - \left(\frac{H_r}{H_{op}} \right) \right]^2 + 4 \left(\frac{H_r}{H_{op}} \right)} \right]$$

Repeat steps (8) to (10) until $\bar{\gamma}_d$ converges to an error of 10^{-3} .

11. Calculate similarity coordinate for "d" streamline

$$\eta_d = \text{erf}^{-1} [2\phi_d - 1]$$

ORIGINAL PAGE IS
OF POOR QUALITY

12. Calculate the geometric parameter $\left[\frac{\sigma \bar{r}}{x \cos \beta} \right]_3$

x = distance along free jet boundary (constant press.)
to point 3

$$\beta = \theta_{3.4}$$

$$\bar{r}_3 = r_w \quad (= 0.5 r_b \text{ by Mingator assumption, see part 3})$$

Jet spread parameter σ

$$\sigma = 12 + 2.758 M_b$$

13. Define integrals

$$I_1(\eta) = \int_{-3}^{\eta} \frac{\rho}{\rho_b} \phi d\eta$$

$$I_3(\eta) = \int_{-3}^{\eta} \frac{\rho}{\rho_b} \phi^2 d\eta$$

for axisymmetric geometry add these \int integrals

$$J_1(\eta) = \int_{-3}^{\eta} \frac{\rho}{\rho_b} \phi \eta d\eta$$

$$J_3(\eta) = \int_{-3}^{\eta} \frac{\rho}{\rho_b} \phi^2 \eta d\eta$$

where $\frac{\rho}{\rho_b} = \left(\frac{C_p}{C_{p_p}} \right) \left(\frac{R_p}{R} \right) \frac{(1 - C_b^2)}{\Lambda' - C_b^2 \phi^2}$

and $\Lambda' = \frac{H_r}{H_{op}} + \left(1 - \frac{H_r}{H_{op}} \right) \phi$

note $\Lambda' = \frac{H_o}{H_{op}}$

$$\frac{C_p}{C_{p_p}} = \frac{C_{p_r}}{C_{p_p}} (1 - \phi) + \phi$$

$$\frac{R}{R_p} = \frac{R_r}{R_p} (1 - \phi) + \phi$$

14. Calculate η_j (coordinate for "j" (jet boundary) streamline)

from the following eqn. [use iterative procedure]
first guess $\eta_j = 1.0$

$$\left[\frac{\sigma \bar{r}}{x \cos \beta} \right]_3^2 - (3.0 - A)^2 = 2A \left\{ I_1(3) - I_1(\eta_j) \right\} + 2 \left\{ J_1(3) - J_1(\eta_j) \right\}$$

where

$$A = \frac{J_3(3) - [J_1(3) - J_1(\eta_j)]}{I_3(3) - [I_1(3) - I_1(\eta_j)]}$$

note $J_1(3) - J_1(\eta_j) = \int_{\eta_j}^3 \frac{p}{\rho_0} \phi(\eta) d\eta$

The above relation comes from the integral momentum & continuity eqns.

$$\int_{-\infty}^{\infty} \rho u^2 dy = u_0 \int_{y_i}^{\infty} \rho u dy$$

$$r = \bar{r} + Y \cos \beta = \bar{r} + (y - y_m) \cos \beta$$

Egn for η_m

$$2(\eta_R - \eta_m) \left(\frac{\sigma \bar{r}}{x \cos \beta} \right) + (\eta_R - \eta_m)^2 = 2 \left(\frac{\sigma \bar{r}}{x \cos \beta} - \eta_m \right) \int_m^{\eta_R=3} \frac{p}{\rho_0} \phi d\eta + 2 \int_m^{\eta_R=3} \frac{p}{\rho_0} \phi \eta d\eta$$

15. Calculate mass flow of secondary / mass flow of primary

$$\boxed{A} \quad \frac{\dot{w}_s}{\dot{w}_p} = \frac{2}{\sigma_2} \left(\frac{x}{r_p} \right)^2 (\cos \beta) \dot{M}_b \left(\frac{P_b}{P_{op}} \right) \frac{\left(\frac{\gamma_p + 1}{2} \right)^{\frac{\gamma_p + 1}{2(\gamma_p - 1)}}}{[1 - C_b^2]^{\frac{1}{2}}} \left[-A(I_1(\eta_j) - I_1(\eta_u)) + (J_1(\eta_j) - J_1(\eta_u)) \right]$$

16. Calculate total enthalpy of secondary / total enthalpy primary

$$\boxed{B} \quad \frac{H_{o, \text{secondary}}}{H_{op}} = \frac{H_r}{H_{op}} + \frac{\left[\frac{H_r}{H_{op}} - 1 \right] \left\{ -A(I_3(\eta_u)) + J_3(\eta_u) \right\}}{\left[-A(I_1(\eta_j) - I_1(\eta_u)) + J_1(\eta_j) - J_1(\eta_u) \right]}$$

17. Calculate Mass fraction of Primary in recirculation region

$$\text{Let } \alpha = \frac{\left\{ -A(I_3(\eta_u)) + J_3(\eta_u) \right\}}{\left[-A(I_1(\eta_j) - I_1(\eta_u)) + J_1(\eta_j) - J_1(\eta_u) \right]}$$

\boxed{C}

$$Y_{pr} = \frac{\alpha}{1 + \alpha}$$

must be satisfied
for converged soln

18. Use Newton's method to solve \boxed{A} , \boxed{B} ,

for unknowns $\frac{P_b}{P_{op}}$, $\frac{H_r}{H_{op}}$

given \dot{w}_s/\dot{w}_p , $\frac{H_{o, \text{secondary}}}{H_{op}}$

update species calculation from \boxed{C}
repeat steps 7-17 with updated Y_{pr}